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Methodology for Estimation of Operational Availability as Applied to Military Systems

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Operational availability (Ao) is an important consideration during the evaluation of system effectiveness and sustainability. Ao is sometimes specified as an attribute within military requirements documents, at the discretion of the proponent. Recently, however, the Chairman of the Joint Chiefs of Staff Manual (CJCSM) 3170C mandated the establishment of materiel availability as a sustainment Key Performance Parameter (KPP). KPPs are defined to be those attributes of a system that are considered critical or essential to the development of an effective military capability. However, test and evaluation of availability is problematic because it is highly dependent on the response and delay times associated with the maintenance and logistics support structures, which are not normally in place prior to fielding. This often leads to the evaluation of Ao via analysis or simulation—measuring the systems reliability and maintainability characteristics—and applying an estimate of the effect of the logistic support system. This article provides a brief background of Ao as well as a comparison of several methodologies for measuring and estimating Ao. Although KPPs are required by CJCSM 3170C to be testable, it is clear that it is necessary in most cases to measure the inherent reliability and maintainability of an item and to apply modeling and/or simulation techniques to evaluate the actual Ao. The equations and methodologies in the article describe the most common of those techniques, as well as their limitations and shortcomings.

Key words: administrative and logistics, corrective and preventive, delay time, downtime, failure frequency, maintenance time, material availability, total active time, uptime.

Operational availability (Ao) is widely used as a readiness-related objective in the specification of requirements for military systems. Its definition can be found in a number of military sources and is fairly consistently represented. (See Sidebar 1)

In general terms, Ao is the proportion of time a system is either operating or is capable of operating (called *uptime*) while being used in a specific manner in a typical maintenance and supply environment. In other words, Ao is the ratio of uptime to *total time*, or more correctly, *total active time*. *Active time* refers to a period in the item's life in which it is being utilized in the environment in which it is intended to perform its primary function. The counterpart, *inactive time*, refers to the period of time in which an item is not being utilized, such as time that it is in storage or being refurbished, or even while undergoing long-range transport (e.g., by sea) or being utilized as a spare or float. Ao is only applicable to active portions of an item's life.

The basic mathematical definition of Ao is

$$\text{Ao} = \text{Uptime/Total (Active) Time}$$

$$(\text{note: active time is assumed from here on})$$

and since an item can be either operable (uptime) or inoperable (*downtime*), mutually exclusively, *Ao* is acceptably defined as shown in Equation 1.

$$Ao = \frac{Uptime}{Uptime + Downtime} \tag{1}$$

Though the definition of *Ao* is fairly straightforward, the calculation of *Ao* can vary somewhat depending on the definitions of uptime and downtime. The inclusion of certain "operational states" can be legitimately expressed as either uptime or downtime; and as long as the definition is clear there can be various "correct" interpretations.

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Sidebar 1: Definitions of Operational Availability (Ao)

At its web site, the Defense Acquisition University (DAU) Glossary of Defense Acquisition Acronyms and Terms defines Ao as "The degree (expressed as a decimal between 0 and 1, or the percentage equivalent) to which one can expect a piece of equipment or weapon system to work properly when it is required, that is, the percent of time the equipment or weapon system is available for use. [Ao] represents system "uptime" and considers the effect of reliability, maintainability, and mean logistics delay time. [Ao] may be calculated by …" [calculation will be covered later in this paper].

(DAU, 2005, website accessed September 12, 2008)

DA PAM 73-1 defines Availability as "the probability that a piece of equipment is in an operable and committable state at a given (random) point in time. Repair, maintenance, and administrative and logistics downtime [ALDT] are the most common causes of equipment non-availability for use. A system's availability is a function of its reliability and maintainability."

(DA PAM 73-1 2003, page 213)

DA PAM 70-3 gives a similar definition "A readiness parameter that is a measure of the degree to which a system is either operating or is capable of operating at any time when used in its typical operational and support environment. Normally, it is most sensitive to the responsiveness of the logistics support system and the system's op-tempo. Because the [materiel developer] has such a principal role in the factors that dominate reliability and maintainability (R&M) and such limited control over the factors that dominate availability, this section is focused on R&M."

(DA PAM 70-3 2008, page 87)

Uptime and downtime

Downtime can be defined as the time during which an item is incapable of performing its primary functions. The most common cause of downtime is a reliability failure and the subsequent maintenance and logistics delays associated with restoring the item to an operational state. The next most common cause is the performance of scheduled maintenance or other maintenance *not necessarily associated with a critical reliability failure* during the performance of which the system cannot be operated.

There are other possible system states, such as relocation time, that are sometimes defined as downtime, but the inclusion of these states as downtime tends to confuse the issue. *Relocation time* is defined as the time spent transporting an item from one place to another in an inert or packaged state, i.e., moving a bulldozer on a trailer from one jobsite to another. True, the bulldozer cannot operate while on the back of a trailer, but neither has the bulldozer lost the capability to perform its primary function—the bulldozer could be used if called upon and unloaded. Categorizing relocation time as downtime unfairly penalizes the item and confuses the issue. If the bulldozer has a low Ao, is it because it is constantly failing or is it because it is frequently transported from jobsite to jobsite? There are other similar categories of time that inherently confuse the issue: setup and teardown time, preventive maintenance checks and services, even re-fueling time can fit in this category. It's much cleaner if downtime is defined to include only that time the system is not functional due to either essential preventive or corrective maintenance, or administrative or logistics delays associated with the repair of reliability failures.

Uptime can be defined as the time an item is capable of performing its primary function if called upon to do so. And, since uptime and downtime are mutually exclusive, uptime is the amount of time left after subtracting downtime from the total available time. (Although technically true, using this approach for estimating *Ao* can lead to erroneous estimates of *Ao*, as will be discussed later.)

In order to properly estimate *Ao*, it is also necessary to further refine the definition of uptime—specifically in such a way as to define the duty cycle of the item. How much of the time is the item expected to operate? This is accomplished by dividing uptime into useful subcategories. The most common of these subcategories are (a) standby time (ST), time in

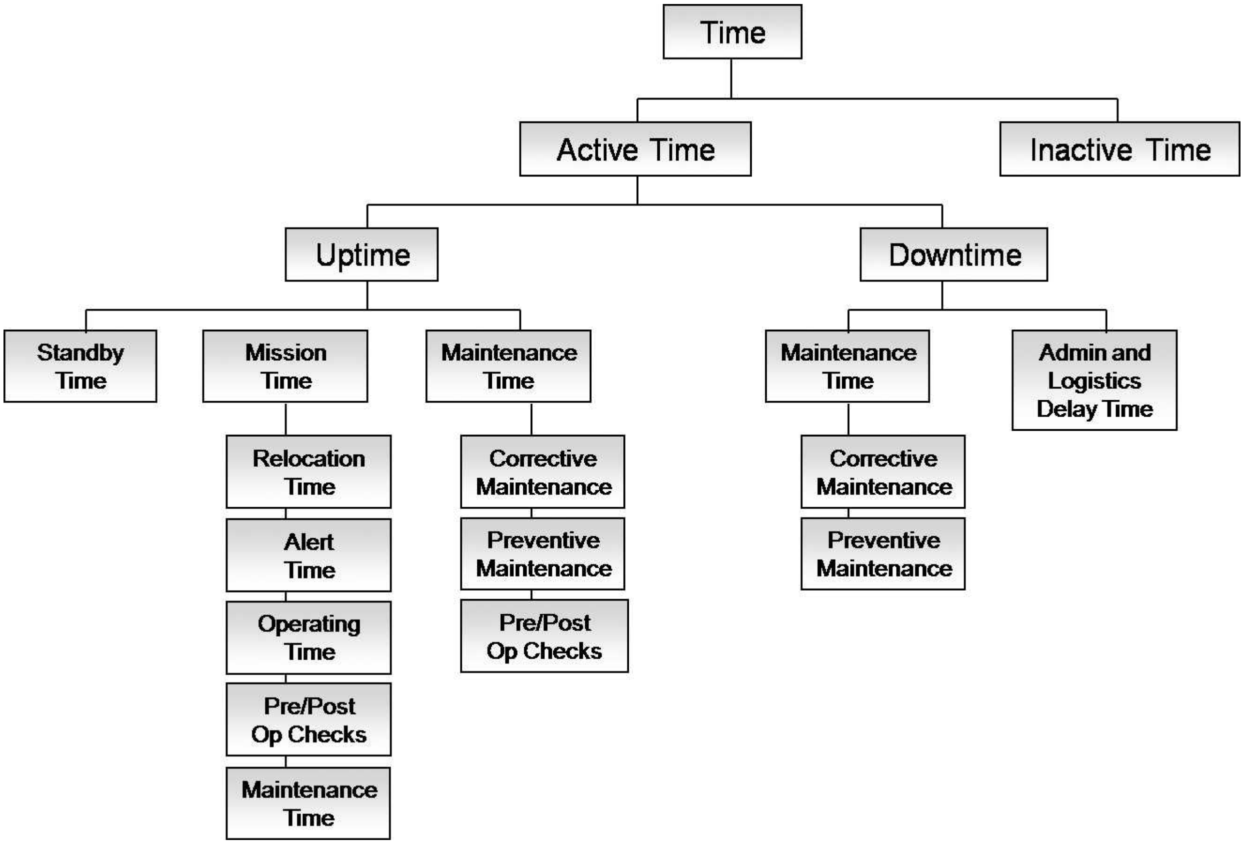

Figure 1. Categories of time for use in defining Ao

which the system is not performing and is not dedicated to performing its primary function; (b) mission time, time in which the system is dedicated to performing its primary function (sometimes incorrectly used interchangeably with operating time); (c) relocation time (defined above); (d) maintenance time, time during which the item is undergoing some scheduled or unscheduled maintenance or pre-/postoperational checks and services; and (e) operating time (OT), time during which an item is actively performing one or more of its primary functions.

There are various ways of defining and organizing these time categories. For example, relocation time can occur either between missions or during a mission, or perhaps both. Maintenance time can occur prior to, after, or during a mission, or any combination thereof.

One common representation of time is shown in *Figure 1* below.

Of all the various time categories, the ones that have the greatest influence on Ao are the OT (since the more the system operates, the more often failures occur), the corrective and preventive maintenance times, and the administrative and logistics delay time (ALDT).

Measurement and evaluation of operational availability

In an operationally realistic test environment, when the actual maintenance and logistics support structures are utilized, the operational availability can be measured by summing the uptime (usually inclusive of OT and ST) and the downtime (usually inclusive of total corrective maintenance [TCM] time, total preventive maintenance [TPM] time, and total ALDT [TALDT]) as shown in Equation 2.

$$Ao = \frac{OT + ST}{OT + ST + TPM + TCM + TALDT} \quad (2)$$

As indicated by DA PAM 73-1, normally the TALDT will greatly outweigh the other factors of downtime. Unfortunately, that is also the hardest parameter to accurately measure during testing. While an item is under development and until well after fielding, the supply system is not fully stocked with spare parts for the item. For test purposes, the contractor normally stockpiles the necessary spare parts so the delay is fairly short, or the opposite occurs and longer-than-normal delays are incurred because the spare parts do not yet exist in sufficient numbers and testing has exhausted the supply.

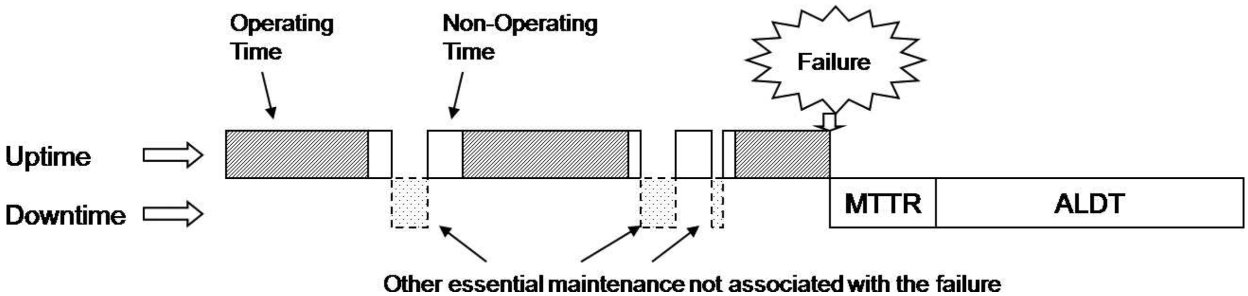

Figure 2. Uptime and downtime distribution

DOD 3235.1-H (1982) states, "One significant problem associated with determining Ao is that it becomes costly and time-consuming to define the various parameters. Defining ALDT and TPM under combat conditions is not feasible in most cases. Nevertheless, the operational availability expression does provide an accepted technique of relating standard reliability and maintainability elements into an effectiveness-oriented parameter."

And, because it is necessary to estimate the *Ao* during the establishment of system requirements, long before any test data is available, an analytical technique is needed to estimate or calculate the expected *Ao*.

Estimation of operational availability

There are three commonly used approaches to the estimation/calculation of *Ao*. The first, using Equation 2, is commonly misused and should be avoided. The results of the other two approaches track fairly well in most cases, but can significantly diverge under certain conditions.

Approach 1: Equation 2

$$Ao = \frac{OT + ST}{OT + ST + TPM + TCM + TALDT}$$

The methodology involved in using Equation 2 to estimate *Ao* for a given calendar time (usually a calendar year) is to

- project the annual *OT* and *ST* (uptime);
- use the projected annual OT and estimated reliability to calculate the annual number of failures expected and thus an annual amount of total corrective maintenance (TCM) time and TALDT (*TCM* = annual *OT/MTBF** mean corrective maintenance time (*MCMT*); *TALDT* = annual *OT/MTBF * ALDT*; where *MTBF* is mean time between failures and *MCMT* is);
- estimate the annual total preventive maintenance (TPM) time;
- sum all uptime (*OT* + *ST*) and downtime (*TCM* + *TPM* + *TALDT*) and plug into Equation 2 to calculate *Ao*.

This approach will almost always result in an incorrect denominator. Because we are calculating *Ao* on an annual basis, the denominator by default has to be one year (8,760 hours). However, in practice one will usually get a denominator either much *larger* or *smaller* than 8,760 hours. Denominators over 8,760 often result because the analyst assumes from the start that *OT* and *ST* together will equal 8,760; the projected downtime is then added to 8,760 to result in an incorrect denominator. When the analyst uses only *OT* to estimate uptime and to project downtime, the resultant denominator can be either larger or smaller than 8,760 hours; only a tiny fraction of the time would the analyst inadvertently obtain an 8,760-hour denominator. Even if that were the case, it's still not the best way to estimate *Ao*.

Approach 2: Subtracting expected downtime from total time

Approach 2 overcomes the denominator issue by initially setting it to the desired value (e.g., 8,760 hours).

Then, because by definition *Uptime = Total Time − Downtime*,

$$Ao = (Total\ Time - Downtime)/Total\ Time.$$

In fact, a commonly used equation can be easily derived, where *TT* is the total time:

$$Ao = \frac{TT - Downtime}{TT}$$

$$Downtime = TPM + TCM + TALDT$$

$$(TCM + TALDT) = \#\text{ of failures} * (MCMT + ALDT)$$

$$(TCM + TALDT) = \frac{OT}{MTBF} * (MCMT + ALDT)$$

$$Ao = \frac{TT - TPM - \frac{OT*(MCMT + ALDT)}{MTBF}}{TT \cdot MTBF}.$$

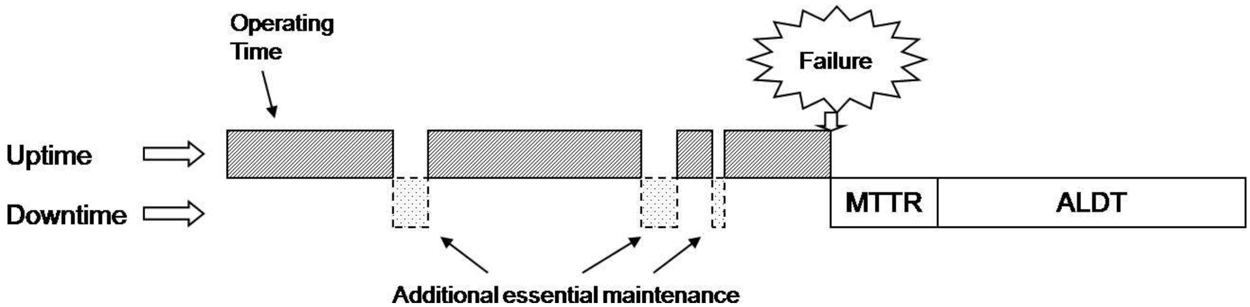

Figure 3. Uptime and downtime for continuously operating system

Dividing numerator and denominator by TT:

$$Ao = 1 - \frac{OT^*(MCMT + ALDT)}{TT^*MTBF} - \frac{TPM}{TT}.$$

Or, because TPM is normally a very small contributor to downtime, the equation is sometimes truncated and represented as

$$Ao = 1 - \frac{OT}{TT} * \frac{(MCMT + ALDT)}{MTBF}. \qquad (3)$$

The derivation is simple and straightforward, but there are problems with this methodology. In certain cases, Equation 3 can result in a negative number! This occurs when the sum of the estimated *OT* and the projected downtime exceeds *TT*. This will occur if the estimated *OT* is a very high percentage of *TT*, or when combinations of reliability and restore times result in significant amounts of downtime. The use of this equation is widespread but can give erroneous results (comparisons of Equation 3 with the results of the third [and preferred] approach will be shown later in this article).

Approach 3: Availability based on failure frequency

Figure 2 shows a normal operate–failure–repair cycle for an item.

The failure annotated in *Figure 2* indicates the occurrence of a *critical* failure—a failure resulting in an item incapable of performing its primary function. Critical failures result in downtime for corrective maintenance as well as administrative and logistics delays. The repair of other *noncritical* failures as well as preventive maintenance is annotated in *Figure 2* as "Other essential maintenance not associated with the failure." Theoretically, noncritical failures may also result in ALDT; however, by their nature the repair of noncritical failures can be deferred until parts arrive—eliminating most if not all ALDT from consideration.

As can be seen in *Figure 2*, the item goes through a period of OT and non-OT, with occasional downtime for miscellaneous essential maintenance, until a critical failure occurs. At that time, the system must be restored to an operational state and, therefore, experiences downtime due to corrective maintenance and administrative and logistics delays. This cycle is continually repeated. Thus, the *Ao* can be represented by a single failure cycle. Ignoring the other essential maintenance (including preventive) for the moment:

$$Uptime = \text{item's } MTBF + \text{non} - OT = MCTBF,$$
$$Downtime = MCMT + ALDT,$$

where *MCTBF* is the mean calendar time between failures.

$$Ao = \frac{MCTBF}{MCTBF + MCMT + ALDT} \qquad (4)$$

The definition of *Ao* in DAU (2008; Reference 1) includes the following: "Ao may be calculated by dividing Mean Time Between Maintenance by the sum of the Mean Time Between Maintenance, Mean Maintenance Time, and Mean Logistics Delay Time (MLDT), that is, Ao = MTBM/(MTBM + MMT + MLDT)."

DOD 3235.1H (1982) contains the same definition, with an important distinction (the note is underlined in the referenced text). "Ao = MTBM/(MTBM + MDT) <u>Note that the above definition assumes that standby time is zero</u>."

Since the majority of downtime is usually associated with unscheduled maintenance, the DAU (2008) expression is often simplified by considering only the unscheduled portion, and of that, only the portion related to correcting failures. Thus, the Reference 1 expression of *Ao* can be reduced to Equation 4, with an important caution. The numerator of Equation 4 is often expressed using the parameter *MTBF* (without the "calendar" time distinction). This leads to the possibility of mistakenly dismissing the standby time as unimportant. This can be a major mistake—in reality, it is the mean *calendar* time between failures that determines the frequency at which downtime occurs.

The *MCTBF* is dependent on the item's *MTBF* and the duty cycle. The item's inherent reliability (*MTBF*)

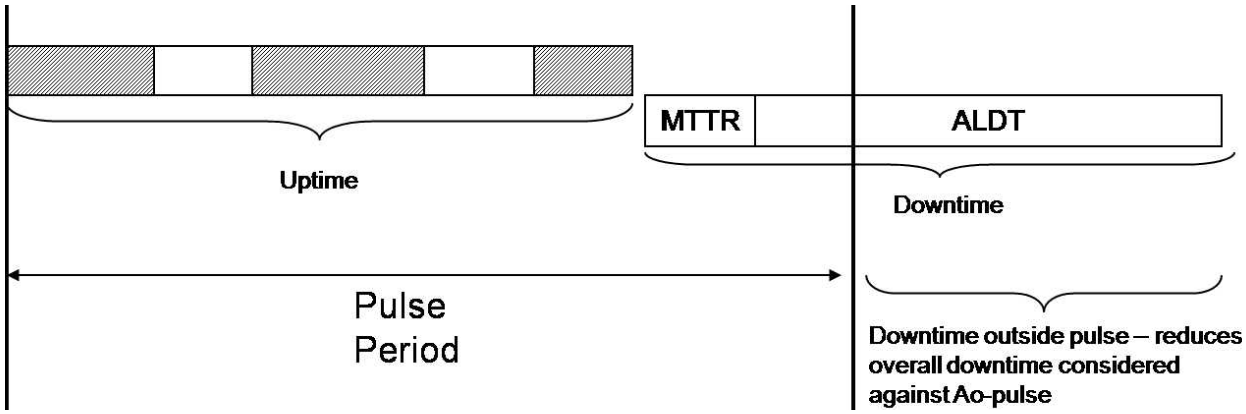

Figure 4. Uptime and downtime for pulse Ao *calculation*

is converted to calendar hours by dividing by the duty cycle, or operating rate (*OPR*). For continually operating systems, *MTBF* = *MCTBF*, but for all others, the duty cycle must be considered. For example, a system with an *MTBF* of 100 operating hours and that operates 12 hours per day (half the time; OPR = 50%) will average 200 calendar hours between failures. In summary, *MCTBF* = *MTBF*/*OPR*.

The additional essential maintenance was excluded from the above discussion because, when included, the estimate of *Ao* will vary somewhat depending on the usage rate and the amount of additional essential maintenance. In *Figure 2*, the additional essential maintenance lowers the uptime and is subtracted from the numerator but does not change the denominator (the calendar time between failures remains the same). This is because in *Figure 2*, there is ample time to perform the additional essential maintenance between usages.

Figure 3 shows another case that represents a continuously operating system.

For a continuously operating system, there is no planned period of nonusage. The *MCTBF* equals the *MTBF* equals the uptime. However, the denominator (which previously was *MCTBF* + *TCM* + *TALDT*) is increased by the amount of additional essential maintenance. It takes longer for the failure to occur, but in the process adds *downtime*, unlike the ST, which increases the *uptime*. Therefore, depending on the situation, the formula for calculation of *Ao* with additional essential maintenance varies—the presentation of other possible alternatives will be discussed in a follow-up to this article.

Choosing an appropriate OPR

The conversion of *MTBF* to *MCTBF* has already been discussed, but it is important to distinguish between and choose the right *OPR* that corresponds to the situation you are trying to represent.

If a system is used intensively part of the year and then used little or not at all the remainder of the year, using the annual *OPR* to estimate *Ao* represents neither the intensive usage period nor the nonintensive period. It might be close to a weighted average, but does not mean much to the casual observer. In a case like this example, the annual *OPR* would not be a good choice. It would be more appropriate to focus on the intensive usage; or calculate parameters for both intensive and nonintensive usage periods. However, if the intensive usage periods are relatively short and spread throughout the year, it is probably acceptable to use the annual *OPR*. The analyst will have to make sure to choose a suitable *OPR*.

Another similar consideration is the calculation of *Ao* for short, intensive usage periods that are followed by low or nonusage periods. This is sometimes referred to as *pulse Ao*. These cases are also very different. *Figure 4* represents a typical pulse *Ao* usage period.

The pulse *Ao* will always be greater than or equal to the steady-state *Ao* because some of the downtime that was induced during the pulse period will extend outside of the pulse period; therefore, it is not counted against the pulse *Ao*. The difference between pulse *Ao* and steady-state *Ao* varies depending on the reliability relative to the pulse period, the relative duration of the downtime, and, of course, the planned usage during the pulse period.

If the *MTBF* is significantly greater than the length of the pulse, there is a high chance of completing the pulse without a failure. Then, a failure will occur only for a small percentage of missions, and only that small percentage of missions will experience any downtime during or extending beyond the pulse. For this case there will not be much difference between the pulse *Ao* and the steady-state *Ao*.

If the *MTBF* is such that there is a good chance of experiencing one or more failures during the pulse and

if the average downtime is also high (relative to the pulse), then a significant portion of downtime can be expected to extend beyond the pulse period, and the pulse *Ao* will differ significantly from the long-term *Ao*.

For situations where many failure–repair cycles occur during the pulse period (i.e., very long pulses or low *MTBF* combined with low downtimes), many failures and repairs can occur during the pulse. In that case, since there are multiple failures and repairs during the pulse, most of the associated downtime occurs during the pulse, and only downtime from the last failure can extend beyond the pulse. In this case, there will be some, but perhaps not significant, difference between the pulse *Ao* and steady-state *Ao*.

There is a methodology developed for consideration and estimation of pulse *Ao*. However, the details and discussion are outside the scope of this article and will be discussed in a follow-up article.

Estimation of operational availability using Approach 3

The remainder of this article will develop equations for calculating steady-state *Ao*, including the consideration of additional essential maintenance, and a separate equation for continuously operating systems. Now, please refer back to *Figure 2*.

For now we will assume that there is enough standby time to accomplish the additional essential maintenance. Thus,

$$Uptime = MTBF/OPR - (\text{amount of additional essential maintenance}).$$

The decision was made to represent the amount of additional essential maintenance in terms of a clock-hour maintenance ratio—the amount of additional essential maintenance is dependent on the amount of operating time. Preventive maintenance is also usually prescribed in terms of both calendar time and usage. Therefore, it is convenient to express our amount of additional essential maintenance as a function of operating time. The clock-hour maintenance ratio for additional essential maintenance (CMR_{ESS}) is expressed in terms of maintenance clock-hours per operating hours. For example, if an item normally operates for 500 hours per month and requires 5 clock-hours of additional essential maintenance downtime (in addition to that for repairs of critical failures), the CMR_{ESS} is equal to 5 clock-hours of maintenance/500 hours of operation = 0.01 maintenance clock-hours per operating hour. Our *OT* during a single failure cycle is equal to *MTBF*. Therefore,

$$Uptime = MTBF/OPR - MTBF * CMR_{\text{ESS}}$$

and

$$Downtime = MCMT + ALDT + MTBF * CMR_{\text{ESS}}.$$

Ao is calculated as the ratio of uptime over total time:

$$\begin{aligned} Ao &= \frac{Uptime}{Uptime + Downtime} \\ &= [MTBF/OPR - (MTBF * CMR_{\text{ESS}})] \\ &\quad \div [MTBF/OPR - (MTBF * CMR_{\text{ESS}}) \\ &\quad + MCMT + ALDT + (MTBF * CMR_{\text{ESS}})] \\ &= \frac{MTBF/OPR - (MTBF * CMR_{\text{ESS}})}{MTBF/OPR + MCMT + ALDT}. \end{aligned}$$

Now dividing numerator and denominator by MTBF and OPR:

$$\frac{1 - (OPR * CMR_{\text{ESS}})}{1 + OPR^*[(MCMT + ALDT)/MTBF]}. \quad (5)$$

Note the uptime was decreased by subtracting the amount of additional essential maintenance. As alluded to earlier, this maintenance time cannot exceed the time remaining after daily operations and has to be completed during the available standby time. We can define an upper limit on the additional essential maintenance, not to exceed the available standby time.

The additional essential maintenance ($MTBF * CMR_{\text{ESS}}$) must be less than the available non-OT:

$$\begin{aligned} \text{Available non}-OT &= MCTBF - MTBF \\ &= MTBF/OPR - MTBF \end{aligned}$$

$$\text{Downtime for addt'l essential maint} = MTBF * CMR_{\text{ESS}}$$

Additional essential maintenance downtime must be less than non-OT:

$$\text{Addt'l essential maint time} \leq \text{non}-OT$$

$$MTBF * CMR_{\text{ESS}} \leq (MTBF/OPR - MTBF).$$

Dividing both sides by MTBF,

$$CMR_{\text{ESS}} \leq 1/OPR - 1.$$

So, if $CMR_{\text{ESS}} - (1 - OPR)/OPR \leq 0$, then Equation 5 can be used.

Now, if the additional maintenance time exceeds the available standby time, we cannot use Equation 5. Therefore, another equation is needed. *Figure 3*, described as the failure cycle description for a continuously operating system, also describes the case where the additional essential maintenance time exceeds the standby time.

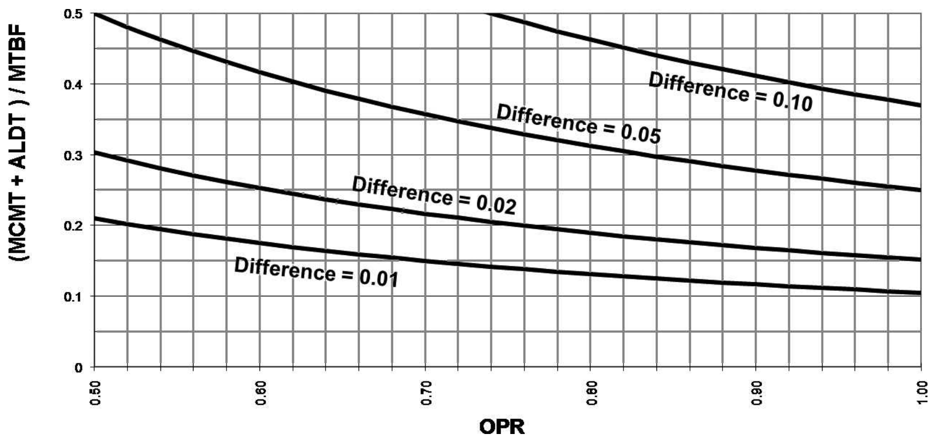

Figure 5. Constant difference between Equations 3 and 6 as a function of reliability, maintainability, logistics delay, and operating rate

This is because, as is true for the continuously operating item, there is no excess non-operating or standby time. What was previously available standby time is now used for additional essential maintenance. Since

$$Uptime = MTBF \text{ and } Downtime = MCMT + ALDT + MTBF * CMR_{ESS},$$

a complementary equation can be easily derived.

Ao is calculated as the ratio of uptime over total time:

$$Ao = \frac{Uptime}{Uptime + Downtime} = \frac{MTBF}{MTBF + MCMT + ALDT + (MTBF * CMR_{ESS})}.$$

Dividing numerator and denominator by *MTBF* gives

$$Ao = \frac{1}{1 + (MCMT + ALDT)/MTBF + CMR_{ESS}} \qquad (6)$$

The results of Equation 3 are always less than Equation 6. However, only under certain circumstances are the differences very significant—that is, when the ratio of average downtime ($MCMT + ALDT$) to *MTBF* is greater than 1/5 and increasing with the OPR. *Figure 5* shows the resultant differences between the two equations (with $CMR_{ESS} = 0$ in Equation 6 for consistency). To use *Figure 5*, look up the intersection of the ($MCMT + ALDT$)/$MTBF$ on the ordinate and the *OPR* on the abscissa—your general location will give an approximate difference as indicated by the lines of constant difference shown on the chart. For example, if our ($MCMT + ALDT$)/$MTBF$ ratio is 0.2, and our *OPR* is 0.76, the intersection hits directly on the 0.02-difference contour line, and we know that the difference between Equations 3 and 6 is 0.02 (with Equation 3 giving the lower result).

Conclusion

The equations described herein provide a technique and methodology for measuring and estimating *Ao*. The results of Equations 5 and 6 and their expansions not covered in this document (including the important pulse *Ao*) closely match results of Monte Carlo simulations written to specifically measure *Ao* over typical operating cycles. Although KPPs are required by CJCSM 3170.01C (2007) to be testable, it is clear that it is necessary in most cases to measure the inherent R&M of an item and apply modeling and/or simulation techniques to evaluate the actual *Ao*. The equations and methodologies in this article describe the most common of those techniques, as well as their limitations and shortcomings. ❏

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